

## Comparison of environmental impact and external cost assessment methods

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### Abstract

**Background, aim, and scope** Impact assessment can be completed with the help of Life Cycle Impact Assessment (LCIA) as a part of Life Cycle Assessment (LCA) and External Cost Assessment methods. These methods help, for project and product classifications, to protect human health and the environment. Comparison of different impact assessment methods along parallel evaluations of real air pollution case studies helps to detect similarities and dependencies between them. The comparison helps and supports the work in both areas by mutually exploiting the merits of both methods. On the other hand, the detected similarities and dependencies also support the accuracy of the assessment work.

**Materials and methods** Two impact assessment methods are compared to detect the dependencies between them. These are: the damage-oriented Life Cycle Impact Assessment method Eco-indicator 99 (EI99) and the Cost-Benefit Analysis (CAFE CBA) carried out within the framework of the Clean Air for Europe Programme of the European Union. Arithmetic comparison of the two methods' impact indicators is carried out in order to show how differently

they assess and evaluate the environmental impacts of the same pollutants. Moreover, air pollution inventories of five industrialized cities in Poland are evaluated in parallel with the two impact assessment methods. The uncertainties of the two methods are also considered and Monte Carlo simulations are completed to obtain probability intervals of impact indicators and overall mean values of the generated populations.

**Results and discussion** The arithmetic comparison of the impact indicators shows a strict correlation between the two impact assessment methods. This correlation is confirmed by results of the parallel evaluation of the real case studies. The comparison of the overall mean values obtained by the Monte Carlo simulations also shows a clear dependency between the results of the two impact assessment methods. After detecting the dependencies between the two methods, the best guess values of the EI99 indicator are selected and applied to make a ranking of the air pollutants and their emission sources for an industrialized Polish city.

**Conclusions** It can be concluded that the detected correlation between the two methods (EI99 and CAFE CBA) supports and helps the accuracy of the impact assessment. If the uncertainties of the methods are also considered, it is proved for the examples of real case studies that they correlate in their results. On the other hand, the best guess of the EI99 indicators can be used to rank emissions according to their relative damage to human health and the ecosystem, and to locate emission sources. These results help decision-makers to conclude an efficient environmental conscious policy.

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## 1 Introduction

The environment is exposed to several pollutants and, among them, air pollution is also an important factor to be considered. Recently, Krupa (2003) has given an overview of air pollution source categories and the effects of these pollutants are being studied by many other scientists. There are several incentives to reduce air pollution since it seriously damages human health and the environment: premature deaths, respiratory diseases, eutrophication, and damage to ecosystems are some of the consequences of this problem. The problem is local, national, international, and transfrontier in nature.

The need for cleaner air has been recognised for several decades with action having been taken at national and European Union (EU) levels, and also through active participation in international conventions. EU action has focused on establishing minimum quality standards for ambient air and tackling the problems of acid rain and ground level ozone. Polluting emissions from large combustion plants and mobile sources have been reduced; fuel quality has been improved and environmental protection requirements have been integrated into the transport and energy sectors. To improve the air quality in Europe, the European Commission launched the Clean Air for Europe Programme (CAFE) in May 2001—a knowledge-based approach with technical/scientific analyses and policy development that will lead to the adoption of a thematic strategy on air pollution, fulfilling the requirements of the Sixth Environmental Action Programme (6th EAP).

The 6th EAP, “Environment 2010: Our future, our choice”, includes “environment and health” as one of the main target areas where additional effort is needed. Air pollution is one of the issues included under environment and health. Whilst overall air quality trends in the Community are encouraging, continued efforts and vigilance are still needed. The Community is acting at many levels to reduce exposure to air pollution: through European Community legislation, through work at a wider international level in order to reduce cross-border pollution, through working with sectors responsible for air pollution such as national and regional authorities, and through research. The focus for the next ten years will be on the implementation of air quality standards and coherency of all air legislation and related policy initiatives ([Clean air and transport; CAFE Programme](#)).

The aim of the CAFE Programme—in agreement with the objective of the 6th EAP—is to develop long-term, strategic and integrated policy advice for “achieving levels of air quality that do not give rise to significant negative impacts on and risks to human health and the environment”; including “no exceedance of critical loads and levels for acidification or eutrophication” (Watkiss et al. 2005).

During air quality improvement incentives, however, it is desirable to have a ranking of the pollutants according to their detrimental impact, either with regard to human health or the environment, while the relevant policies are being created. Such a ranking of the pollutants’ impacts should detect the most dangerous ones and, along with this, their sources of origin. The basis for such a ranking is the scientific assessment of the environmental impacts caused by the pollutants. There are several methods and incentives to assess and quantify environmental impacts using different impact pathway approaches and impact indicators.

Cost-benefit analysis is an economic tool supporting decision-making through monetary valuation. Environmental damages are converted into costs—generally on the basis of Paretian’s welfare theory, in which individuals confronted with external effects judge their importance for their quality of life. The evaluation of damages is performed in one single category: currency. The position of the CBA indicators in the cause-effect chain is at the damage level.

Life Cycle Assessment (LCA) is the only standardized tool currently used to assess environmental loads of products and processes. Life Cycle Impact Assessment (LCIA), as a part of LCA, is a scientific technique for assessing the potential impacts of products on the environment (Wrisberg et al. 2002; Sonnemann et al. 2004). Environmental damages are assessed in several impact categories, (i.e. human toxicity, use of natural resources, global warming, ozone depletion, acidification, eutrophication, smog formation, land use, noise), each with a category indicator (Wenzel et al. 1997; Jolliet et al. 2003; Finkbeiner et al. 2006). Environmental impacts in the different impact categories can be compared and summed up, whereby environmental impacts can be expressed by aggregated scores.

According to Jolliet et al. (2003, 2004), LCIA methods can be classified as (1) classical or midpoint-based impact assessment methods, and (2) damage oriented or endpoint-based (single score) methods. Classical impact assessment methods restrict quantitative modelling to relatively early stages in the cause-effect chain to limit uncertainties. LCA results are presented for several damage categories (midpoint categories). Damage-oriented methods try to model the cause-effect chain up to the endpoint, sometimes with high uncertainties. Application of midpoints at the interpretation of LCA results has several advantages: it exposes the multi-dimensionality of the problem of environmental assessment; it does not require additional steps of data collection, modelling and computation; it makes possible the iterative evaluation of impact indicators and exclusion of indicators with too high uncertainty. However, midpoint-based LCA results are often too complex; but the aggregation of different impacts into a single number

makes the interpretation and communication of the results to stakeholders easier and it is therefore often desired by decision-makers (Lenzen 2006). Moreover, Life Cycle Initiatives, the joint project of UNEP (United Nations Environment Programme) and SETAC (Society for Environmental Toxicology and Chemistry), also recognised the need for shifting the interpretation of LCA results in the direction of the more easily interpretable endpoint-based approaches instead of the more complex midpoint approaches. A comprehensive LCA framework is under construction which combines the classical methods with the damage-oriented methods in order to utilize the benefits of both approach types (Jolliet et al. 2004, 2005).

The eco-indicator 99 Life Cycle Impact Assessment Methodology (EI99) is a frequently applied damage-oriented LCIA method, which was originally developed for product design and which is probably the most relevant to European industrial pollutions (Goedkoop and Spriensma 2000; Hofstetter et al. 2003; Dreyer et al. 2003; Benko et al. 2006).

A newly developed impact assessment method and framework has been introduced by the European Union (EU) in order to assess environmental impacts caused by air pollution, and to analyse scenarios generated within the CAFE Programme. The cost-benefit analysis (CBA) within the framework of the EU's CAFE Programme (CAFE CBA) tries to deliver a fair and accurate set of estimates of the effects (marginal damages) of air pollution on health and ecosystems (basically exposure of crops to ozone), Holland et al. 2005a. The CAFE CBA has been carried out and results have been published in form of damages per tonne of emissions of major air pollutants for the EU25 member states excluding Cyprus (Holland et al. 2005b). The application of marginal damage values obtained by the CAFE CBA for the evaluation of an air pollution inventory in order to determine the most significant air pollutants and their sources in a particular European city is well substantiated. The CAFE CBA results are available for five major pollutants.

Several research works aim to study the possible differences and similarities between impact assessment methods in order to provide help through the selection of the proper methods, i.e. van der Werf and Petit (2002), Dreyer et al. (2003), (Bovea and Gallardo 2006). The differences and similarities were explored through the parallel evaluation of the same case studies with the different impact assessment methods.

In this work, two significant and important incentives for the assessment and evaluation of environmental impacts of polluting materials are selected: the results of the CAFE CBA, supported by the European Union, and the Eco-indicator 99 Life Cycle Impact Assessment Method. It is suspected that there must be similarities between the two

methods and such similarities and dependencies between the two methods are to be detected, since this might help support the work in both areas as it would enable one to mutually exploit the merits of both methods. Moreover, the efficiency of LCIA in environmental policy making is demonstrated with a case study: EI99 indicators are applied to make a ranking of the air pollutants and their emission sources for an industrialized Polish city.

## 2 Data and methods

The two LCIA methods investigated are: (1) EI99 and (2) CAFE CBA. The similarities and dependencies between the two methods are researched through arithmetic comparison of the two methods' impact indicators, and through the parallel environmental impact assessment of the same environmental case studies.

Arithmetic comparison is carried out on XY-type comparative charts: impact indicators of the two methods are plotted against each other for each air pollutant. Results are evaluated with correlation analysis.

At the parallel evaluation, real case studies are evaluated with both of the methods and results are compared on comparative charts. In our consideration, a real environmentally-oriented project should be considered as a basis for the investigation. The evaluation of the pollution registers of Polish cities are selected in order to identify the pollution sources with the highest environmental impacts.

The EU suggests the application of the CAFE CBA results for policy making. The damage-oriented LCIA methods like EI99 are less popular among LCA experts because of the high data uncertainties; however, impact indicators for more pollutant species are available in the EI99 than in the CAFE CBA, which could make the analysis more detailed.

### 2.1 Emission inventories

The project of the Emission and Health Unit, Institute for Environment and Sustainability, Joint Research Centre (JRC), Ispra, entitled "From toxic emissions to health effects—an integrated emissions, air quality and health impacts case study Krakow", delivers real data on air quality in Polish cities. Polish partners and the Institute of Prospective Technological Studies, Seville, have also participated in this project.

Several air pollution data have been collected, measurements have also been taken to determine pollution levels and their health effects. The pollution data are summarised in an emission inventory. The methodology for setting up the emission inventory is based on the recommendations of the UN ECE Task Force on Emission Inventory and

Projections. Different databases are used for the determination of the emissions inventory, such as, for example, the EMEP/CORINAIR Emission Inventory Guidebook, State Centre of Emission Inventory in Warsaw, Main Statistical Office of Poland (NILU Polska and IEIA 2005).

Table 1 shows the pollutants included into the emission inventory and the pollutant sources according to Selected Nomenclature for Air Pollution (SNAP) codes.

The emission inventory was set up for the year 2002 on the level of administrative units. The emission inventory completed for the selected cities consists of data gathered by source and split by SNAP code.

Emission factors for all processes listed according to their SNAP code are developed on the basis of data taken from the national emission inventory. For the calculation of the individual emissions, regional data based on different activities are also determined and used.

Table 2 shows the results of the calculations. The pollutants are listed by source (NILU Polska and IEIA 2005). Pollutant source identifiers can be found in Table 1. The pollutants highlighted with grey background are involved in the comparison of the CAFE CBA and EI99 methods. It should be noted that, in approximately 10% of all households, coal is used for heating purposes.

## 2.2 Eco-indicator 99

The Eco-indicator 99 (EI99) is a damage-oriented approach to LCIA which models the cause-effect chain up to the damage (endpoint) and expresses the environmental impact

**Table 1** Pollutants included in the emission inventory and their sources according to their SNAP codes

Pollutants	Pollutant sources
P1. SO <sub>2</sub>	S1. District heating
P2. NO <sub>x</sub>	S2. Combustion in the housing and commercial sector, individual heating
P3. CO	S3. Combustion in agriculture
P4. NMVOC	S4. Road transport
P5. CH <sub>4</sub>	S5. Other transport
P6. NH <sub>3</sub>	S6. Household use of paints and solvents
P7. Dioxins and furans (combined according to TEQ index)	S7. Land filling
P8. PAH (including benzo(a)pyrene)	S8. Agricultural waste burning
P9. PM (d>10 µm, 10>d>2.5 µm, d<2.5 µm); indicated as TSP, PM <sub>10</sub> , and PM <sub>2.5</sub> .	S9. Emission from crops S10. Farming

with a single score, the so-called Eco-indicator point. There is no absolute value for the indicators; they only have a relative value: similar processes might be compared based on the Eco-indicator points. The scale of Eco-indicators is chosen in such a way that the value of one point is equal to 1/1000 of the yearly environmental load of the average European inhabitant (Goedkoop and Spriensma 2000; Koning et al. 2002).

EI99 considers three endpoints: (1) Human Health, (2) Ecosystem Quality, and (3) Resource Depletion. This impact assessment methodology consists of two parts: (i) the scientific calculation of the several forms of environmental damage, and (ii) a valuation procedure to establish the significance of these damages. The scientific calculation step characterises the environmental load of a single pollutant with the “best guess” value obtained through damage modelling. The “best guess” values are referred to as eco-indicator points (EI99 points). The valuation procedure includes a normalisation and a weighting step for the three damage categories. In the normalization step, the environmental impacts determined in the calculative steps are related to a reference system. Weighting supports the evaluation of the normalised damage indicators from several aspects: LCA experts can consider the three damage categories during the impact assessment with different user-defined weights based on their individual choices.

Impact assessment in the Human Health and Ecosystem Quality categories consists of fate, exposure, effect, and damage analysis. The fate model EUSES (1996) is used for modelling the dispersion of carcinogenic and/or ecotoxic pollutants; substances that cause respiratory effects are modelled with atmospheric deposition models and empirical observations, as described by Hofstetter (1998); for acidification and eutrophication, the GIS-based multi media-model and the SMART model (A Simulation Model for Acidification’s Regional Trends, Kros et al. (1995)), developed by the RIVM (The Dutch National Institute for Public Health and the Environment), are used.

The impact analysis for substances causing respiratory problems (among others, NH<sub>3</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, SO<sub>2</sub>, and VOCs) follows an epidemiological approach based on data obtained from Hofstetter (1998). The impact analysis for substances causing acidification/eutrophication (among others, NH<sub>3</sub>, NO<sub>x</sub>, SO<sub>2</sub>) is carried out on the basis of the Hazard Unit concept (Bakker and van de Meent 1997).

For the quantification of damages to Human Health, the Disability Adjusted Life Years (DALY) concept, originally developed for the WHO and World Bank, is used. In the damage category Ecosystem Quality, Potentially Affected Fraction (PAF) of species and Potentially Disappeared Fraction (PDF) of species indicate the extent of the environmental damage.

**Table 2** Calculated emission values for several cities in the neighbourhood of Krakow [t/year]

Cities	Sources:	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Krakow	NH <sub>3</sub>	0	0	0	0	0	0	168	0	66	78
	NO <sub>x</sub>	366	495	12	4,739	205	0	0	0	0	0
	PM <sub>2.5</sub>	39	458	8	341	20	0	0	1	0	0
	SO <sub>2</sub>	1,509	1,779	29	699	10	0	0	0	0	0
	NMVOC	46	830	12	2,513	115	3,354	0	1	0	0
	CO	282	13,865	203	12,743	296	0	0	615	0	0
	CH <sub>4</sub>	2	315	5	89	1	0	11,123	1	0	148
	Dioxin <sup>a</sup>	0.007	1.814	0.002	0.013	0.0002	0	0	0.004	0	0
	PAH <sup>b</sup>	7	1,080	16	27	1.1	0.22	0	0	0	0
	TSP	323	1,269	20	1,081	20	0	0	1	0	9
Bielsko-Biala	PM <sub>10</sub>	161	989	16	376	20	0	0	1	0	4
	NH <sub>3</sub>	0	0	0	0	0	0	48	0	13	27
	NO <sub>x</sub>	74	125	2	1,103	41	0	0	0	0	0
	PM <sub>2.5</sub>	8	116	2	79	4	0	0	0	0	0
	SO <sub>2</sub>	267	172	5	68	3	0	0	0	0	0
Katowice	NMVOC	9	210	2	585	23	763	0	0	0	0
	NH <sub>3</sub>	0	0	0	0	0	0	99	0	11	9
	NO <sub>x</sub>	154	581	2	2,075	112	0	0	0	0	0
	PM <sub>2.5</sub>	17	538	1	149	11	0	0	0	0	0
	SO <sub>2</sub>	637	2,091	5	306	6	0	0	0	0	0
Kielce	NMVOC	19	976	2	1,101	63	1,627	0	0	0	0
	NH <sub>3</sub>	0	0	0	0	0	0	53	0	17	27
	NO <sub>x</sub>	145	66	3	1,077	137	0	0	0	0	0
	PM <sub>2.5</sub>	16	61	2	78	13	0	0	0	0	0
	SO <sub>2</sub>	597	236	8	159	7	0	0	0	0	0
Nowy Sacz	NMVOC	18	110	3	571	77	919	0	0	0	0
	NH <sub>3</sub>	0	0	0	0	0	0	24	0	11	36
	NO <sub>x</sub>	65	48	2	460	49	0	0	0	0	0
	PM <sub>2.5</sub>	7	44	1	33	5	0	0	0	0	0
	SO <sub>2</sub>	307	450	6	163	2	0	0	0	0	0
Opole	NMVOC	8	80	2	244	27	315	0	0	0	0
	NH <sub>3</sub>	0	0	0	0	0	0	41	0	24	65
	NO <sub>x</sub>	105	99	4	849	67	0	0	0	0	0
	PM <sub>2.5</sub>	11	91	3	61	6	0	0	0	0	0
	SO <sub>2</sub>	432	356	10	125	3	0	0	0	0	0
	NMVOC	13	166	4	450	38	574	0	0	0	0

<sup>a</sup> g/year<sup>b</sup> kg/year

The EI99 method is acknowledged as being a standard investigation tool for LCA and is applied in about one hundred countries. The application of the EI99 is supported by different LCA expert software tools.

Main advantage of this method is the easy manner of interpretation of the results supporting mostly the comparison of alternative product or service systems for internal use. If compatibility with ISO is required, it should be kept in mind that weighting is not allowed within ISO

14042 (2000) for comparative assertions disclosed to the public.

Uncertainties in the EI99 can be distinguished and separated as: (i) data uncertainties, and (ii) model uncertainties. Data uncertainties refer to technical problems of measuring and assessing factors in the calculation step of the methodology, and are presented as squared geometric standard deviation values in the manuals of EI99. Model uncertainties refer to the uncertainty of the model being

configured incorrectly including assumptions on time horizon, manageability of problems, required level of evidence for environmental damage, location, etc. According to Goedkoop and Spriensma (2000), model uncertainties cannot be expressed as a range; the assumptions of a model are correct or not. In order to cope with this type of uncertainty, a system referred to as Cultural Theory is used to separate three versions of the damage models. A simplified characterisation of the three versions is the following. E (Egalitarian): long time perspective; even a minimum scientific proof justifies inclusion. I (Individualist): short time perspective; only proven effects are included. H (Hierarchist): balanced time perspective, consensus among scientist determines inclusion of effects (Goedkoop and Spriensma 2000; Koning et al. 2002).

In this study, the hierarchist version of the EI99 method with a custom weighting set is selected, which assumes 50% weight for both the Human Health and the Ecosystem Quality damage categories. Since air pollution has no direct effect on the natural resources, this damage category is not included. Table 3 shows the best guess EI99 indicator points per tonne of airborne emissions and the squared geometric standard deviation applied in this study.

### 2.3 CAFE marginal damage

The “Service Contract for Cost-Benefit Analysis of Air Quality Related Issues, in particular in the Clean Air for Europe Programme” has been established in order to carry out the assessment of the costs and benefits of air pollution policies (estimation of the impacts of air pollutants and their control options), and to conduct analysis on scenarios

**Table 3** Eco-indicator points of 1 tonne airborne emissions and squared standard deviation values (n/a=not applied in the study). Eco-indicator 99 hierarchist version, with 50–50% weighting for the damage categories of Human Health and Ecosystem Quality

	Best guess	$(\sigma_g^2)$
NH <sub>3</sub>	4,285	98
NO <sub>x</sub>	3,446	116
PM <sub>2.5</sub>	22,785	19
SO <sub>2</sub>	1,878	78
VOC	17	23
CO	11	n/a
NMVOC	42	n/a
CH <sub>4</sub>	144	n/a
NH <sub>3</sub>	4,285	n/a
Dioxin	5.9E+09	n/a
PAH	5,600	n/a
TSP	3,580	n/a
PM <sub>10</sub>	12,200	n/a

generated within the CAFE programme. The CAFE CBA was created to support political decision-making with reference to the future in the European region (Holland et al. 2005a).

The CAFE CBA impact assessment methodology quantifies and evaluates the environmental impacts caused by fine particles (PM<sub>2.5</sub>) and ground-level ozone (O<sub>3</sub>) according to the impact pathway approach developed in the ExternE project funded by the European Commission Directorate-General for Research (ExternE). The quantification of the exposure and the impacts is based on UN health statistics and data; the valuation of the impacts is carried out using world market prices, and from a “willingness to pay” perspective. The CAFE CBA methodology uses the Euro/tonne pollutant impact indicator.

Holland et al. (2005b) carried out an impact assessment using the CAFE CBA methodology resulting in the assessment and valuation of the external costs and benefits of anthropogenic air pollution as regards five major air pollutants (NH<sub>3</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, SO<sub>2</sub>, and VOCs). They provided the marginal damages per tonne of pollutants taking into consideration variations in the emissions sites and providing estimates for each EU 25 Member state (excluding Cyprus) and for the surrounding seas.

The reported marginal damage values are based on modelling a uniform relative reduction in emissions of each pollutant within each country. Dispersion modelling was carried out with the EMEP model with 50×50 km resolution, with updated chemistry and meteorology. Model simulations were carried out for each of the five air pollutants, considering direct and indirect effects of the pollutants on the fine particle and ground level ozone concentrations. The considered and quantified impacts include (i) human exposure to PM<sub>2.5</sub> considering chronic effects on mortality and morbidity, and acute effects on morbidity; (ii) human exposure to ozone considering acute effects on mortality and morbidity, and (iii) exposure of crops to ozone considering yield loss for several industrial crops.

Holland et al. (2005b) presented total damages from each of the five pollutants with four sets of assumptions at the impact assessment including different assumptions on mortality, core health and crop functions, sensitivity of health functions and ozone impacts. The change in magnitude of marginal damages for the central scenarios is largely a reflection of the values used for the mortality valuation, rather than a response to other sensitivities explored. Therefore, the arithmetic mean of the four marginal damage values referring to one pollutant is also considered and used as a best estimation of the marginal damages caused by the other pollutants. The low and upper ends of the analyses are used as minimum and maximum values referring to each pollutant. Table 4 shows the

**Table 4** CAFE marginal damage per tonne emission (Euro/tonne) with different sets of sensitivity analyses, and the overall mean value. Data refer to Poland

CAFE marginal damage values					
PM mortality	VOLY-median	VSL-median	VOLY-mean	VSL-mean	Arithmetic mean
O3 mortality	VOLY-median	VOLY-median	VOLY-mean	VOLY-mean	
Health core?	Yes	Yes	Yes	Yes	
Health sensitivity?	No	No	Yes	Yes	
Crops	Yes	Yes	Yes	Yes	
O3/health metric	SOMO 35	SOMO 35	SOMO 0	SOMO 0	
NH <sub>3</sub>	10,000	15,000	20,000	29,000	18,500
NO <sub>x</sub>	3,900	5,800	7,100	10,300	6,775
PM <sub>2.5</sub>	29,000	44,000	57,000	83,000	53,250
SO <sub>2</sub>	5,600	8,600	11,000	16,000	10,300
VOCs	630	960	1,500	2,000	1,273

marginal damage per tonne emission with the different sets of sensitivity analyses and arithmetic mean of the four marginal damage values. CAFE CBA marginal damage values in Table 4 refer to Poland.

### 3 Discussion and results

The impact assessment methods are based on different impact pathway approaches. Their application and, in particular, the interpretation of the results can be complicated due to a number of factors (i.e. spatial effects, time horizon, uncertainty of data or models, etc.) Therefore, it is necessary to evaluate the effect of these factors. In this work, the effects of the uncertainties and the similarities and differences between CAFE CBA and EI99 are explored based on an existing air pollution case study completed by the JRC.

Emission data published by NILU Polska do not contain information on the impacts of the different pollutants or the pollutant sources. If the environmental impacts are assessed based on the CAFE CBA or on the EI99 methodology, the following problems could occur. The CAFE CBA is a newly developed and frequently applied method which, however, only provides the environmental impacts of five pollutants. On the contrary, with the EI99, all pollutants included in the NILU Polska database can be evaluated; however, uncertainties in the eco-indicator scores can make the evaluation of the results more difficult. In certain cases, the clear environmental preferences cannot even be even concluded due to them.

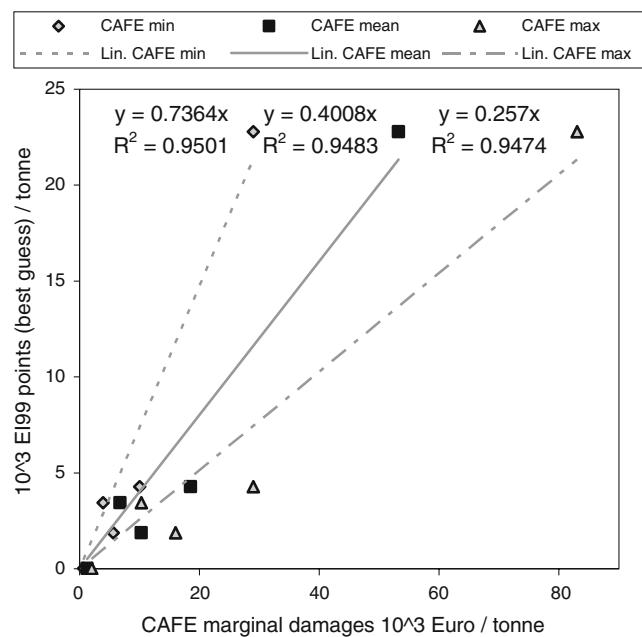
#### 3.1 Comparison of CAFE CBA and EI99 impact indicators

Arithmetic comparison of the impact factors is carried out: minimum (diamonds), maximum (triangles) and arithmetic mean (squares) marginal damage values are plotted against EI99 points (“best guess”) considering the five pollutants in

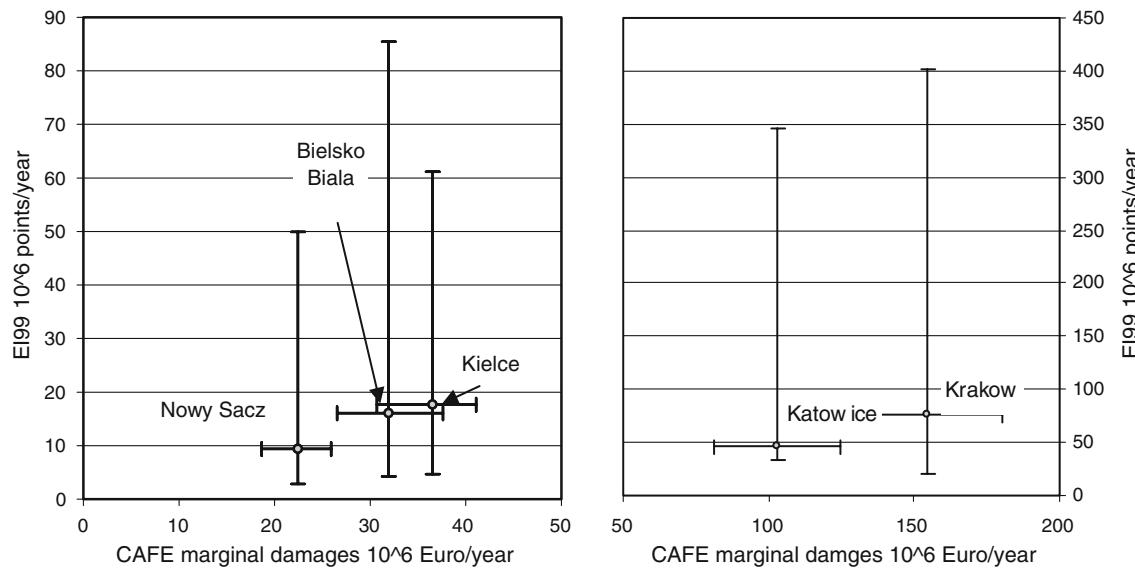
Fig. 1. Linear trend lines are fitted to the three impact indicator pairs. The correlation between the two methods in the valuation and ranking of the environmental impacts caused by the selected air pollutants is clearly shown with R-squared values higher than 0.94 in all cases. This confirms both the acceptability of the linear trend and the strong correlation between the Eco-indicator points and the marginal damage values. The fact that the R-squared value is similarly high in all three cases leads to the conclusion that the coherence between EI99 and CAFE CBA results does not depend on a set of indicators of the CAFE CBA.

#### 3.2 Evaluation of air pollution in Polish cities

The consistency between the two methods can be further explored if they are applied in parallel for the evaluation of



**Fig. 1** EI99 points against CAFE CBA results (minimum, maximum and overall mean values). Impacts per tonne emission of air pollutants



**Fig. 2** Impact indicator intervals obtained by Monte Carlo simulation. Results are shown for five Polish cities

several emission inventories. A theoretical case is assumed: the ranking of the five cities is desired on the basis of air pollution-driven environmental impacts. Environmental impacts caused by air pollution of five Polish cities are assessed and evaluated based on the EI99 and CAFE CBA methods. The emission inventories of the cities are provided in Table 2. The reference unit is the annual environmental impacts caused by air pollution.

The effects of the uncertainties related to the impact indicators are also analysed. A number of impact indicators is generated through a Monte Carlo simulation performed (10,000 iterations at a confidence level of 95%). The environmental impact indicators are summarized for all pollutants and pollution sources included in the emission inventories (Table 1). Uncertainty intervals referring to the different EI99 points are calculated based on the best guess values and geometric standard deviation ( $\sigma_g^2$ ) data assuming lognormal distribution (Table 3). Lower and upper limit of the 95% confidence intervals are calculated by the formula: EI99 indicator \*  $(\sigma_g^2)^{\pm 1}$ .

Since no quantitative uncertainty data is published for CAFE CBA results, the minimum and maximum marginal damage values are considered as lower and upper limit of the interval assessing the environmental impacts.

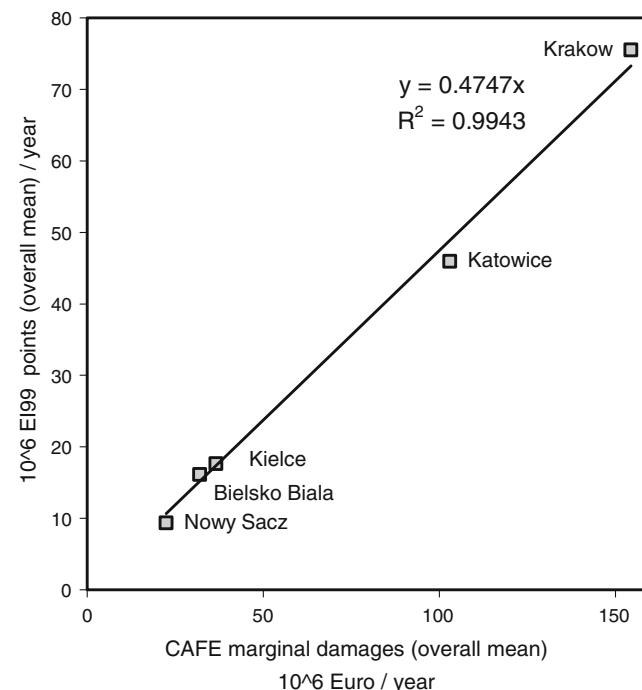
These calculative steps result in impact indicator intervals expressing the magnitude of the environmental impacts in each city studied. The indicator intervals calculated with CAFE CBA and EI99 indicators are shown in Fig. 2.

The CAFE CBA results give discrete impact assessment intervals for the annual air pollution in Nowy Sacz, Katowice, and Krakow which supports the formation of judgements on overall air pollution in the different cities. In the case of

Bielsko Biala and Kielce, impact indicator intervals significantly overlap, i.e. the city with higher environmental impacts due to air pollution cannot be identified.

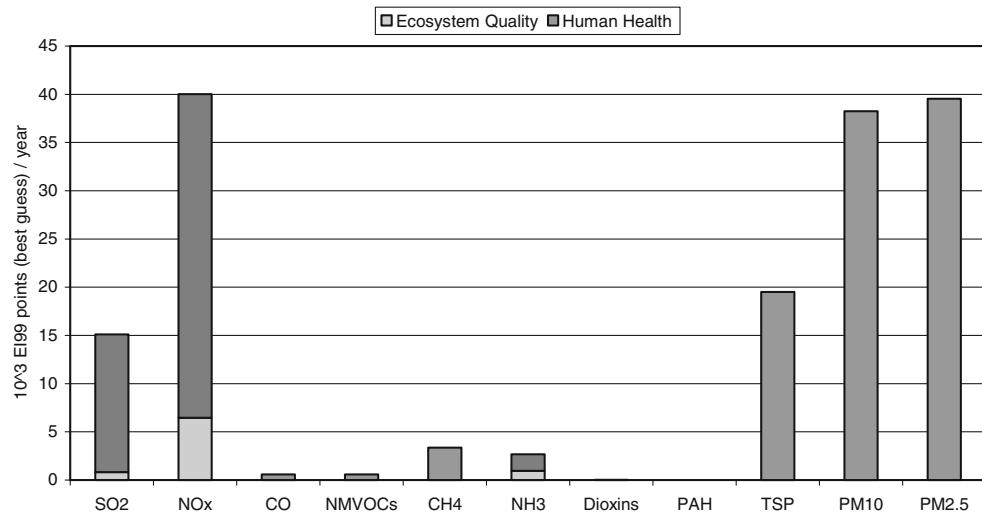
Intervals of environmental impacts assessed by EI99 overlap widely, which makes the set up of clear preferences between the alternatives (cities) impossible.

According to former studies (i.e. Lenzen 2006; Basson and Petri 2007), propagation of uncertainty in damage-



**Fig. 3** Overall mean values of population of impact indicators obtained by Monte Carlo simulation. Results are shown for five Polish cities

**Fig. 4** Environmental impacts of Krakow city relating to air pollutants. Results are obtained by EI99 (evaluating 11 pollutants)



oriented impact indicators can lead to a situation where no ordinal ranking between different alternatives can be established. In this study, inclusion of uncertainty in the evaluation of the emission registers does not facilitate any decision-making. Taking into consideration valuation uncertainties in the results, one should try to provide clear interpretations to stakeholders.

According to this, the overall mean values of the impact indicator populations generated by the Monte Carlo simulation are determined. The results obtained through the impact assessment based on the two LCIA methods are plotted on the same diagram for each city; results are shown in Fig. 3.

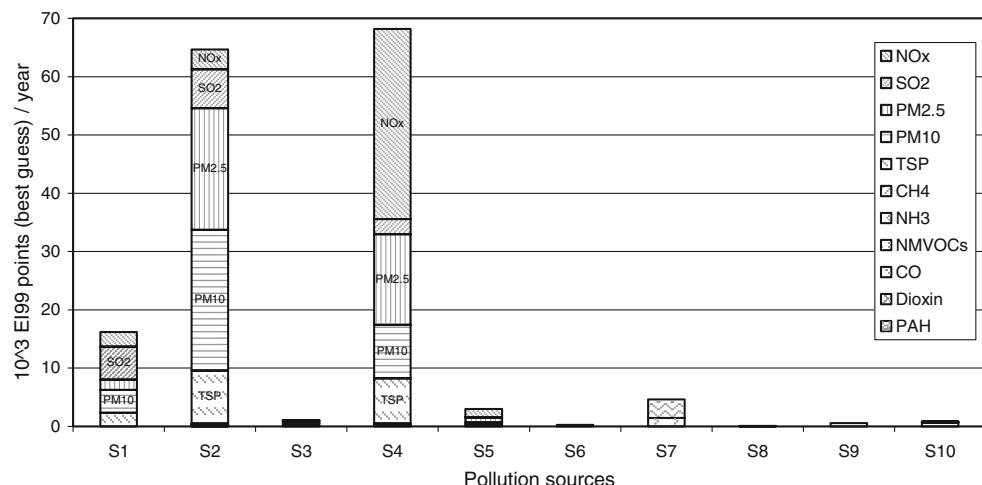
A very strong correlation can be found between these data i.e. the overall mean values of the generated population of indicators show a strong correlation between the two methods. When a linear trend line is fitted to the points, the coefficient of determination ( $R^2$ ) is higher than 0.99, which confirms the reliability of the fit and the strong correlation

between the two methods. This means that the applied version of EI99 and CAFE CBA, despite of the differences in their impact assessment pathway and damage models, does not show significant difference in practice, the two methods give very similar results (i.e. the ranking of the five cities) for the studied cases. It can be concluded that the two impact assessment methods can mutually support and strengthen each other's merits. Moreover, the detected correlation between the two methods can help the investigation and development of both methods in the future, since such activities can be co-ordinated.

### 3.3 Analysis and ranking of air pollution of an industrialized city based on Eco-indicator points

As a case study, the environmental impacts caused by the annual emission of air pollutants from several sources in Krakow are assessed and evaluated based on the EI99 method. The former analysis is extended: all 11 air

**Fig. 5** Environmental impacts of Krakow city relating to pollution sources. Results are obtained by EI99



pollutants registered in the NILU database are considered and evaluated. The emission inventory is shown in Table 2. The results of such a study can serve several purposes, i.e. the identification of the sectors and the air pollutants with the highest environmental load in the investigated city. For the evaluation of the results, it should be noted that this data is regional and that household heating is based on coal used.

Figure 4 shows the contribution of the studied air pollutants to the total annual environmental impacts in the damage categories Human Health and Ecosystem quality. According to the current weighting set, environmental impacts are mostly related to Human Health while Ecosystem Quality contributes less than 10% to the total impact. The most dangerous of the studied pollutants are the fine particulates, NO<sub>x</sub>, and SO<sub>2</sub>. Environmental impacts caused by particulate matters are caused mainly by the individual heating sector (56%), and road transport (33%); impacts related to NO<sub>x</sub> is originated mainly from road transport (81%); environmental impacts of SO<sub>2</sub> are caused mainly by the individual (44%) and district (37%) heating sectors.

Figure 5 shows the environmental impacts caused by the different pollution sources. A ranking of the polluting activities can be performed: the most polluting activities for the considered pollutants following the chosen weighting methodologies are traffic (road transport), and individual heating. It should be mentioned that this pollution ranking highlights the problem that individual heating based on coal is more polluting than district heating, since there are no emission limitations for such small combustion alternatives. This evaluation, on the one hand, helps to locate the most polluting activities and, on the other hand, helps the policy makers to find proper decisions for the installation of air quality improvement facilities.

#### 4 Conclusions

The comparison of the two impact assessment methods shows that the methods deliver similar results, in spite of their basically different impact pathway approaches. This result can be interpreted in several areas of the environmental research and policies: the research work for the development of the two impact assessment methods can mutually support each other—the detected correlation can be used by the elaboration of further CAFE CBA indicators either by the assessment of a new CAFE CBA indicator using extrapolation or by the validation of the new CAF CBA indicators. Moreover, the application of the two methods shows that they deliver similar results and it depends on the problem to be analysed which of the two is going to be applied.

Considering that the EI99 currently has a larger database, it can cover more problems but, on the other hand, the CAFE CBA delivers the results in monetary units.

Since the comparison of the two environmental impact assessment methods (EI 99 and CAFE CBA) shows a clear dependency between the overall mean values of CAFE CBA and the best guess of EI99 for the considered case study, it can result in a further conclusion that the application of these single score indicators (omitting the uncertainty data) can deliver clear environmental preferences. This can help to make proper decisions for their use and for the interpretation of their results.

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#### References

- Bakker J, van de Meent D (1997) Receptuur voor de berekening van de indicator effecten toxicische stoffen (Itox). RIVM report 607504003
- Basson L, Petri JG (2007) An integrated approach for the consideration of uncertainty in decision making supported by life cycle assessment. Environ Model Softw 22:167–176
- Benko T, Szanyi A, Mizsey P, Fonyo Z (2006) Environmental and economic comparison of waste solvent treatment options. CEJC 4(1):92–110
- Bovea MD, Gallardo A (2006) The influence of impact assessment methods on materials selection for eco-design. Mater Des 27:209–215
- CAFE Programme, home page: <http://europa.eu.int/comm/environment/air/cafe/>
- Clean air and transport, home page: <http://ec.europa.eu/environment/air/index.htm>
- Dreyer LC, Niemann AL, Hauschild MZ (2003) Comparison of three different LCIA methods: EDIP97, CML2001 and eco-indicator 99. Int J LCA 8:191–200
- EUSES (1996) : EUSES the European Union System for the Evaluation of Substances. National Institute of Public Health and Environment (RIVM), The Netherlands. Available from the European Chemicals Bureau (EC/JRC), Ispra, Italy
- ExternE, home page: <http://www.externe.info/>
- Finkbeiner M, Inaba A, Tan RBH, Christiansen K, Klüppel HJ (2006) The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int J LCA 11:80–85
- Goedkoop M, Spriensma R (2000) The eco-indicator 99, a damage oriented method for life cycle impact assessment, methodology report, pre consultants, the Netherlands
- Hofstetter P (1998) Perspectives in life cycle impact assessment; a structured approach to combine models of the technosphere, ecosphere and valuesphere. Kluwers Academic Publishers.
- Hofstetter TB, Capello C, Hungerbühler K (2003) Environmentally preferable treatment options for industrial waste solvent management - a case study of a toluene containing waste solvent. Trans IChemE 81, Part B, 189–202
- Holland M, Hunt A, Hurley F, Navrud S, Watkiss P (2005a) Service contract for carrying out cost-benefit analysis of air quality related issues, in particular in the Clean Air for Europe (CAFE)

- Programme, Vol. 1–3. AEA Technology, homepage: <http://www.cafe-cba.org>
- Holland M, Pye S, Watkiss P, Droste-Franke B, Bickel P (2005b) Damages per tonne emission of PM<sub>2.5</sub>, NH<sub>3</sub>, SO<sub>2</sub>, NO<sub>x</sub> and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas, Service contract in CAFE Program. AEA Technology, homepage: <http://www.cafe-cba.org>
- ISO 14042, (2000) Environmental management—life cycle assessment—life cycle impact assessment, technical standard. International Standards Organization, Geneva, Switzerland
- Jolliet O, Margin M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) IMPACT 2002+: A new life cycle impact assessment methodology. *Int J LCA* 8:324–330
- Jolliet O, Müller-Wenk R, Bare J, Brent A, Goedkoop M, Heijungs R, Itsu N, Peña C, Pennington D, Potting J, Rebitzer G, Stewart M, Haes HU, Weidema B (2004) The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. *Int J LCA* 9:394–404
- Jolliet O, Dubreuil A, Gloria T, Hauschild M (2005) Progresses in life cycle impact assessment within the UNEP/SETAC life cycle initiative. *Int J LCA* 10:447–448
- Koning A, Guinée J, Pennington D, Sleeswijk A, Hauschild M, Molander S, Nyström B, Pant R, Schowanek D (2002) Methods and typology report part A: inventory and classification of LCA characterisation methods for assessing toxic releases. Contribution to work-package 7 of the OMNIITOX Project as part A of appropriate deliverable D11
- Kros K, Reinds GJ, Vries W de, Latour JB, Bollen MJS (1995): Modelling of soil acidity and nitrogen availability in natural ecosystems in response to changes in acid deposition and hydrology. Report 95; SC-DLO; Wageningen
- Krupa S (2003) Atmosphere and agriculture in the new millennium. *Environ Pollut* 126:293–300
- Lenzen M (2006) Uncertainty in impact and externality assessments implications for decision-making. *Int J LCA* 11:189–199
- NILU Polska Ltd., Inst. for Ecology of Industrial Areas (IEIA) (2005): Report on compilation of emission inventories and synthetic emission scenarios for the Krakow integrated project.
- SimaPro 7, homepage: <http://www.pre.nl/simapro/default.htm>
- Sonnemann G, Castells F, Schuhmacher M (2004) Integrated life-cycle and risk assessment for industrial processes. CRC Press LLC, Boca Raton, Florida. ISBN 1566706440
- van der Werf HMG, Petit J (2002) Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. *Agric Ecosyst Environ* 93:131–145
- Watkiss P, Pye S, Holland M (2005) CAFE CBA: baseline analysis 2000 to 2020
- Wenzel H, Hauschild M, Alting L (1997) Environmental assessment of products - methodology, tools and case studies in product development. Chapman & Hall, London, United Kingdom
- Wrzesberg N, de Haes HAU, Triebswetter U, Eder P, Clift R (2002) Analytical tools for environmental design and management in a systems perspective. Kluwer Academic Publisher, Dordrecht, The Netherlands